IDENTIFICATION OF NDE METHODS FOR INSPECTION OF MULTI-LAYER CERAMIC COMPOSITE ARMOR

T.J. Meitzler
US Army, TARDEC
Warren, MI

L. P. Franks
US Army, TARDEC
Warren, MI

W. A. Ellingson and E.R. Koehl
Argonne National Laboratory
Argonne, Illinois USA

J. S. Steckenrider
Illinois College
Jacksonville, IL

ABSTRACT

In order to establish a preferred NDE method for quantifying damage within multi-layered ceramic composite armor, an Effects of Defects project has been established using a series of 84 16-inch square by 2-inch thick, tiles together with an array of various NDE methods. Some of the armor tiles have had ‘designed defects” built in during manufacture, mainly delaminations, inserted within the interior and selectively positioned between various layers. All samples are planned to be ballistically tested at the Aberdeen Army Research Laboratory, (ARL), and are to be inspected by an array of NDE methods before and after ballistic testing. The planned outcome of this project is to identify which NDE modality might best be used to quantify ballistically-induced damage in composite ceramic armor. NDE modalities to be used include: 1)-immersion phased array ultrasonics, 2)- through-transmission, direct-digital x-ray imaging, 3)-non-contact scanning microwaves, 4)-air-coupled ultrasound and 5)-immersion, through-transmission and pulse-echo single-transducer ultrasound. At this time, all of the 84 samples have been prepared, have been inspected and ballistic testing completed. This paper will discuss the overall project and includes the test samples planned, the test schedule planned, an overview of the NDE techniques to be used and will briefly discuss results obtained .

INTRODUCTION

Recently, a project was undertaken by the US Army to assess several nondestructive evaluation technologies for detection of ballistically-induced damage in multi-layer, ceramic composite armor. The objective is to demonstrate the capability or limitations of various NDE methods to detect disbond-type defects through use of a carefully controlled set of test specimens that have intentional disbond-type flaws of various sizes and locations within the test samples. Shown below in Figure 1 is a schematic diagram of a cross section of a multi-layered ceramic composite armor used in this effort. . To be noted is that ceramic tile is “sandwiched” between two thinner layers of special material and this “sandwich’ is followed by a layer of an elastomer and then flowed by a thicker layer of a low-elastic modulus material.

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
08 JAN 2010	**N/A**	**-**

4. TITLE AND SUBTITLE **A Identification of NDE Methods for Inspection Multi-Layer Ceramic Composite Armor**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **J. S. Steckenrider; W. A. Ellingson; E.R. Koehl; T.J. Meitzler; L. P. Franks**	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Illinois College Jacksonville, IL, USA Argonne National Laboratory Argonne, Illinois USA US Army RDECOM-TARDEC 6501 E 11 Mile Rd Warren, MI 48397-5000, USA**	8. PERFORMING ORGANIZATION REPORT NUMBER **20482RC**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) **TACOM/TARDEC** 11. SPONSOR/MONITOR’S REPORT NUMBER(S) **20482RC**

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
Presented at 34th International Conference and Exposition on Advanced Ceramics and Composites (ICACC), 24-29 January 2010, Daytona Beach, FL, USA, The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**9**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

From the NDE standpoint, such an armor design presents challenges for inspection. The ballistic impact side is the “sandwich’ side and the low elastic modulus material side is the side that is mounted to the vehicle. In this project, the NDE methods to be explored were not restricted to those with the potential for “on-vehicle’ inspection potential. Rather the NDE methods selected were those that seemed appropriate for inspection of as-produced armor appliqués and appliqués that have been removed from vehicles..

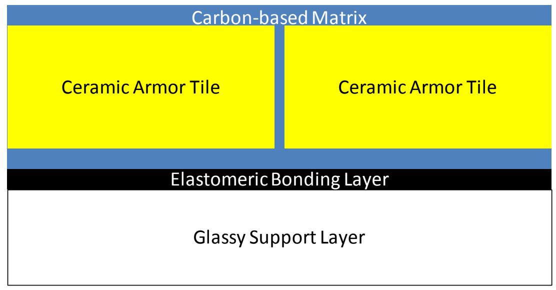
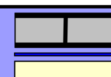
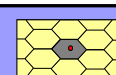
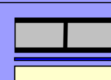
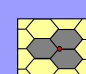
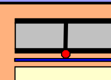
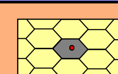
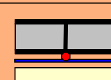
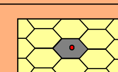
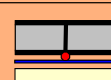
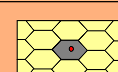
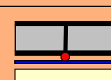
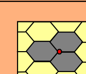
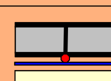
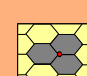
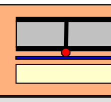
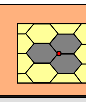
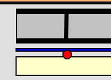
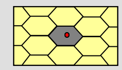
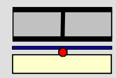
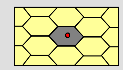
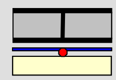
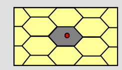
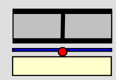
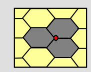
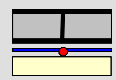
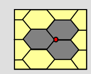
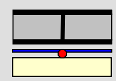
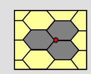


Figure1. Schematic diagram of cross section of multi-layer ceramic composite armor

The NDE methods under evaluation include: 1)-immersion phased array ultrasonics, 2)- through-transmission, direct-digital x-ray imaging, 3)-non-contact scanning microwaves, 4)-air-coupled ultrasound and 5)-immersion, through-transmission and pulse-echo single-transducer ultrasound. In order to evaluate these NDE methods, a set of 84 specially made ceramic composite samples was made for these tests. Table I shows the list of samples along with schematic diagrams of the various designs.

Table I: List and schematic diagrams of NDE Effects of Defects samples

Run Designation	Panel Designation	Description	Panel Qty	Flaw Size	Flaw Position	Center/Triple Pt
A	A1-A4	Baseline - Center	8	No flaws		
B	B1-B4	Baseline - TP	8	No flaws		
C	C1-C4	Graphite to Rubber	8	½” square		
D	D1-D4	Graphite to Rubber	8	1½” square		
E	E1-E4	Graphite to Rubber	8	2½” square		
F	F1-F4	Graphite to Rubber	8	½” square		
G	G1-G4	Graphite to Rubber	8	1½” square		

H	H1-H4	Graphite to Rubber	8	2½" square		
J	J1-J4	Rubber to S2	8	½" square		
K	K1-K4	Rubber to S2	8	1½" square		
L	L1-L4	Rubber to S2	8	2½" square		
M	M1-M4	Rubber to S2	8	½" square		
N	N1-N4	Rubber to S2	8	1½" square		
O	O1-O4	Rubber to S2	8	2½" square		

To be noted is that the inserted 'defects" are placed either above the layer immediately behind the ceramic insert or placed below the layer following the ceramic insert. In addition, the sizes of the defects inserted varied from 12 mm square (1/2-inch) to 62 mm square (2 ½-inches) . Fabrication of the armor test panels further utilized two different ceramic materials. A slightly higher density and different composition material was used in the immediate vicinity of the inserted defects, see gray region in schematics of Table I, and a lower density ceramic material was then used for all surrounding tile (the yellow regions in the schematics of table I). It is the overall plan to develop NDE capability to effectively estimate the flaw size and location in ceramic armor in order to support survivable structures for) Ground Combat Vehicles (GCV's).

PLAN/SCOPE OF WORK

The scope of work as defined has nine tasks: These include:

Task 1.0 –– Manufacture multi-hit test panels

Task 2.0 – Conduct initial NDE studies

Task 3.0 – Manufacture 50 multi-hit test panels with and without intentional defects

Task 4.0 – Conduct initial NDE prior to ballistic impact testing

Task 5.0 – Ballistically impact test panels

Task 6.0 – Manufacture 112 single shot panels

Task 7.0 –Conduct "best-effort" NDE studies of single shot panels

Task 8.0 – Ballistically impact, single shot,   84 test panels

Task 9.0 - Conduct radiography NDE tests on all 84 ballistically impacted test panels

The fabrication of the intentional defect test panels will follow the flow chart of Figure 2. An example of

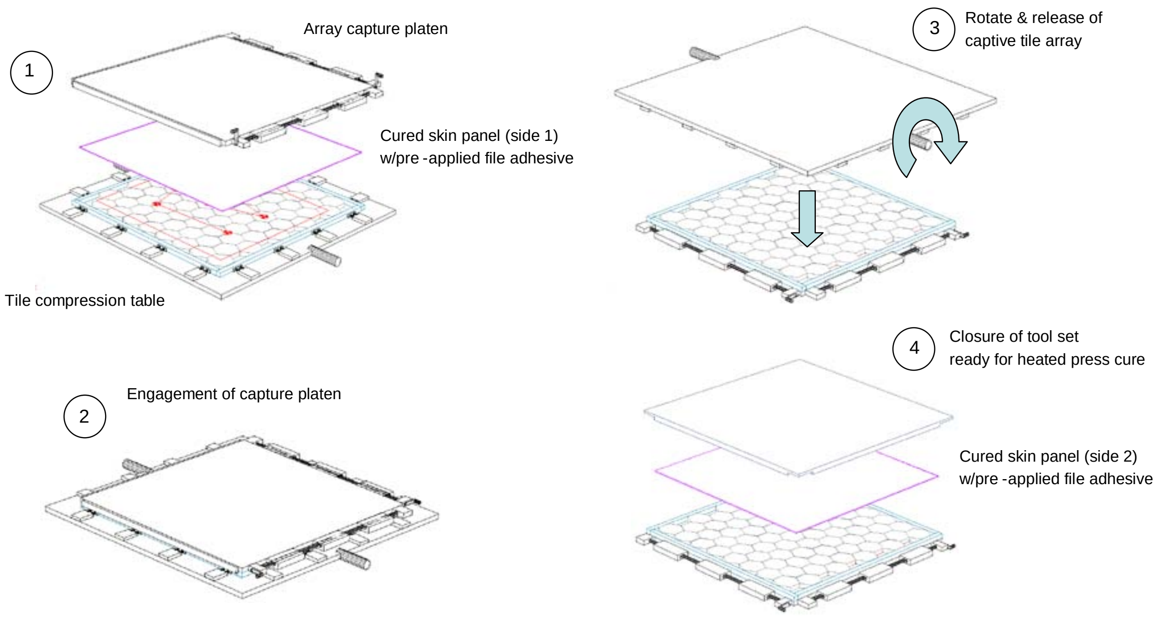


Figure 2. Schematic diagram of flow chart for fabrication of intentional defect test panels for NDE

what a partially completed test panel looks like is shown in Figure 3. The photograph shows one of the test panels that is a "'triple point" sample and has three silicon carbide ceramic test blocks surrounded by aluminum oxide test blocks. These panels were then cut to yield four test panels each with three silicon carbide blocks in the center as noted in Table I.

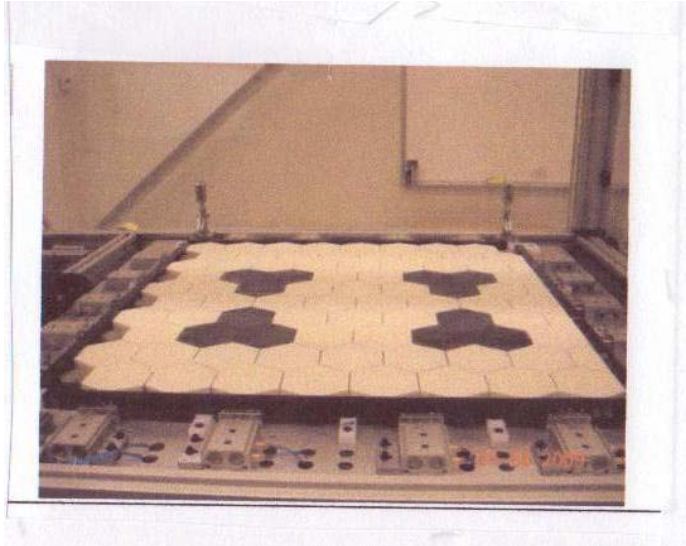


Figure 3: Photograph of intentional defect test panel during fabrication. The three darker

Tiles shown in four locations are the silicon carbide tiles used for the ‘triple point” samples.

DESCRIPTION OF THE NDE METHODS

The following section briefly describes the several nondestructive evaluation (NDE) methods that have been identified as methods to be explored in this effort.

1. Immersion Phased Array Ultrasonics

The selection of phased array ultrasonic methods (refs 5,6,7), was chosen as a method because this method was used discussed previously for application to ceramic armor and was shown to demonstrate capability for defect detection. However, all previous work was conducted on the ceramic material itself and not in the presence of any other material as these samples are. It is known that in a layered structure with several different materials and hence different acoustic velocities, refraction of the acoustic wave will occur and effects of this on defect detection is unknown. However, previous work on defect detection in armor quality ceramics clearly demonstrated that a much higher signal to noise ratio (S/N) was obtained for a phased array system as compared to a single-transducer immersion ultrasound system. Shown below in Figures 4 are photographs of the immersion phased-array ultrasound system used in this study. This system can drive a phased array transducer with up to 128 individual elements with control of the sequence of up to 32 elements at any one time.

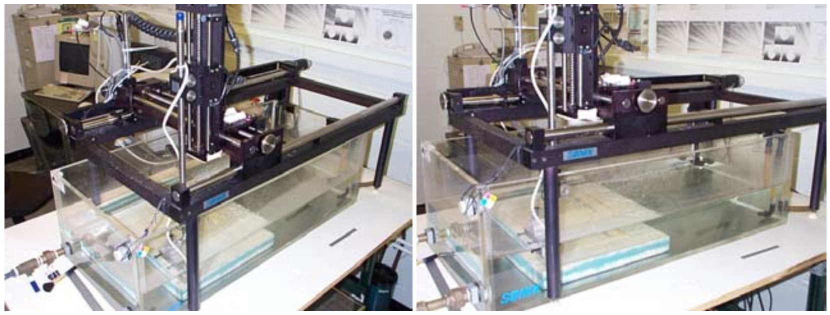


Figure 4: Photographs of immersion Phased Array Ultrasound equipment

The importance of using phased array technology for inspecting these ceramic composite armor tile is that by selecting the firing sequence of the transducer elements, the depth of the focus can be dynamically changed. This is shown schematically in Figure 5.   By focusing at a well defined depth within the sample, the signal to noise ratio of the detected reflected pulse can be significantly increased.

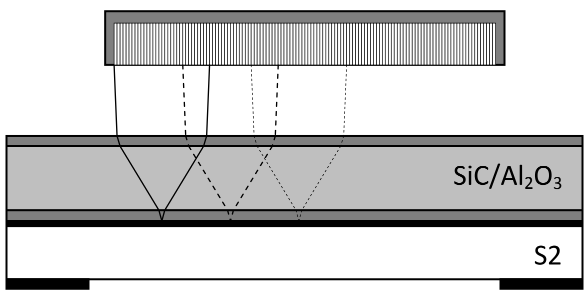


Figure 5: Schematic diagram showing firing sequence of the phased-array transducer with insonification from the "graphite" side with the focus at the graphite to rubber interface. (horizontal dimensions not to scale). Although inspection insonification from both ballistic impact side (as shown here) and armor mounting side have been conducted, all data presented has been insonified from the ballistic impact side .

2) Through Transmission, Direct-Digital, X-ray Imaging

Through-transmission, direct digital x-ray imaging systems using state-of-the-art flat panel detectors was selected for testing because past experience had also shown this to be a viable NDE method for crack detection in armor ceramics. The authors have shown that use of a 420 KVp x-ray head coupled to a large area, 17-inch by 17-inch, flat panel detector could detect cracks in thick layered structures. A set-up for x-ray imaging is shown in Figure 6. The flat panel detector has 2048 200 um square pixels.

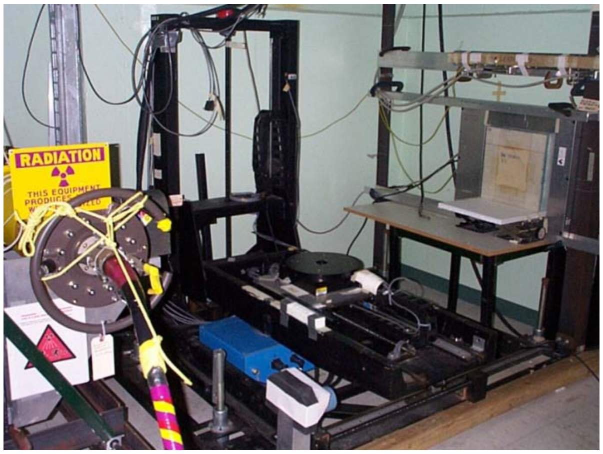


Figure 6: Photograph of X-ray imaging equipment

3. Scanning Microwave Methods

Scanning microwave methods were selected based on recent past results for flaw detection in armor ceramics. In addition, scanning microwave technology has been demonstrated to be able to detect damage in ceramic composite armor while that armor is still mounted on the vehicle. Scanning microwave technology however is a new NDE technology. In this method, see Figure 7, a microwave interference pattern is created by irradiating the part in microwave energy. By raster scanning the probe containing the transmitter and receiver is raster-scanned over the part, the detected signal is displayed on a computer screen. The different voltage values represent differences in the local dielectric constant.

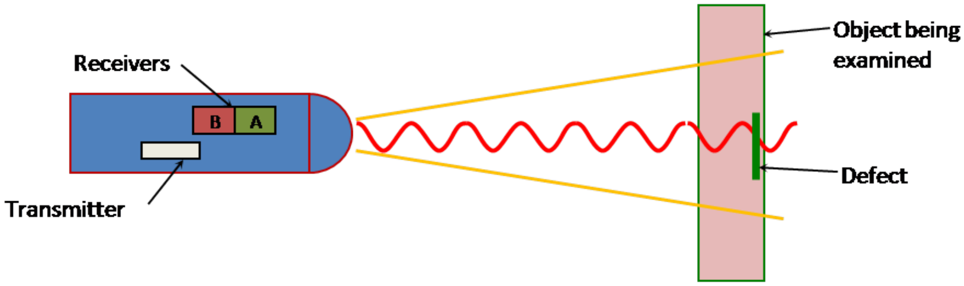


Figure 7: Schematic diagram showing relative position of microwave transmitter and receiver head to the part under examination. One-sided access is shown.

4. **Immersion, Single Transducer, Scanning Ultrasound**

The selection of immersion ultrasound was based on past work that demonstrated defect detection in ceramic armor similar to the prior work using phased array immersion ultrasound. Immersion ultrasound using a single transducer is a long time method that is well-establish but has the same issue with layered materials as does phased array—that is in a layered structure with different materials and different acoustic velocities, refraction of the incident acoustic wave takes place thus (Refs 4,5) these effects on flaw detection is unpredictable. A single-transducer ultrasonic scanning system is similar in every way to the phased array scanning ultrasound system with the exception that the transducer is not a phased array transducer. As opposed to the phased array, the single transducer cannot be focused at different positions within the object unless the stand-off distance between the transducer and the test part is changed. Thus to scan with the "focus" of a single transducer , one must make several scans and in between scans the stand-off distance has to be changed. This usually results in very long data acquisition times as compare to phased array scans.

5. **Air Coupled Ultrasonic methods**

The last NDE method selected, air-coupled ultrasound, is a relatively new technology and is one NDE method that perhaps has potential for "on-vehicle" armor damage evaluation provided that significant issues with acoustic energy insertion can be overcome because "on-vehicle" requires one-sided inspection. Air-coupled ultrasound has a significant advantage in that it eliminates the need for any liquid coupling between the test object and the ultrasonic probe. However, the method is limited to use in the through-transmission mode because of the low acoustic energy insertion. Further, because of issues with fabrication, usually air-coupled transducers are limited to frequencies less than 1 MHz. The limitations imposed by use of low frequencies thus also limits the defect size that can be detected. However, it was decided to explore this method to establish the limitations.

RESULTS

At the present time, the 84 single shot test panels have been fabricated and all 84 have been inspected by all NDE methods.

CONCLUSIONS

In conclusion, 84 specially made ceramic composite armor test panels have been produced as part of a special project to establish which NDE methods might better detect defects in such armor systems. Several forms of ultrasonic testing have been used: Immersion phased array, immersion single focused transducers, air-coupled systems. Further, two x-ray imaging systems have been explored: one using a large area flat panel and one using a small area flat panel. Scanning microwaves were also explored but presently suffer from the fact this method is unusable if an electrical conducting layer is employed in a layered armor structure. It seems that phased array ultrasound and use of large-area, direct-digital projection x-ray imaging offers the most time and cost effective NDE technologies for armor ***not*** mounted on vehicles.

REFERENCES

[1]J.S. Steckenrider, W.A. Ellingson, and J.M. Wheeler, Ultrasonic Techniques for Evaluation of SiC Armor Tile , *Ceramic Eng. And Sci. Proc.* 26(7) 215-222 (2005)

[2]W. A. Ellingson and M. W. Vannier , Applications of Dual-Energy X-Ray Computed Tomography to Structural Ceramics,in Proc. 37th Ann. Denver Conf. on *Advances in X-Ray Analysis*, , ed. C. S. Barrett, J. V. Gilfrich, R. Jenkins, T. C. Huang, and P. K. Predecki, Plenum Press, NY, 629-640 (1989)

[3] K. Schmidt, J. Little and W. Ellingson, A portable microwave scanning technique for nondestructive testing of multilayered dielectric materials", Proc. 32nd Inter. Conf. & Expos. on Adv. Ceramics and Composites, (2008)

[4]Y. Ikeda., K.Onda, and Y. Mizuta, Nondestructive Evaluation of Porosity in Si3N4 Ceramics by using Ultrasonic method, in *Proc. Of the 4th Symposium on Ultrasonic Testing, JSNDI*,105-108 (1997)

[5]Nondestructive testing handbook, 2nd ed., Vol 7—Ultrasonic Testing, P. McIntire, Ed. Am Soc. For Nondestructive testing (1991)

[6]T. A. K. Pillai, W. A. Ellingson, J. G. Sun, T. E. Easler , and A. Szweda, A Correlation of Air-Coupled Ultrasonic and Thermal Diffusivity Data for CFCC Materials, in *Ceramic Engr. and Sci. Proc., Vol. 18, Issue 4 (1997).*

[7]W.A. Grandia and C. M. Fortunko, NDE applications of air-coupled ultrasonic transducers, in *Proc. IEEE Ultrasonic symposium*, Vol.1, 697-709(1995)